

## ENGINEERING TOMOGRAPHY: A QUANTITATIVE NDE TOOL

Richard L. Hack, Donna K. Archipley-Smith,  
and William H. Pfeifer

PDA engineering, 1560 Brookhollow Drive  
Santa Ana, CA 92705

### BACKGROUND

The development and application of advanced materials, whether composite, metal matrix or ceramic, has progressed to a point where qualitative non-destructive inspection of components is no longer sufficient. As confidence in the validity of material properties increases, structures utilizing these advanced materials will be designed without the excessive safety factors characteristic of earlier structures utilizing the same materials. While this trend has the advantage of economizing on the use of the advanced, expensive materials, it underscores the need to quantify the flaw structure of advanced material components so that accurate, flawed material thermostructural response can be predicted and so that a quantified accept/reject criteria for a given component can be established.

Engineering tomography is an overall engineering tool and plan to achieve the quantified accept/reject criteria previously mentioned. Engineering tomography should be viewed as a collection of 4 subcomponents.

- Obtain quantitative digitized NDE data (i.e. X-ray CT, digital ultrasonics, magnetic resonance imaging) of a component to locate and identify flaw structure.
- Establish material property data base with degraded material properties as a function of the physical measured property obtained with the quantitative NDE inspection.
- Construct a 3-dimensional finite element model of the component including flaws (location and size) noted with the quantitative NDE technique.
- Conduct a finite element analysis on the flaw laden model integrated with the degraded material property data base to obtain a defective component response and ultimately quantify the acceptability or rejectability of the component.

As a whole, engineering tomography should prove to be a very powerful quantitative NDE tool. All of these steps need to be addressed to make engineering tomography a reality. The first step, quantifying flaws and the effects of flaws, is the focus of this paper.

Recent progress in the field of NDE has resulted in a number of techniques that go a long way to achieving the quantitative inspection required; techniques such as x-ray computed tomography (CT), advanced and digital ultrasonics (UT), magnetic resonance imaging (MRI) and advanced X-ray fluoroscopy all go a long way to improving our quantitative understanding of flaw structure.

## EXPERIMENTAL APPROACH

One approach to developing quantitative accept/reject criteria is shown schematically in Figure 1. At the present time, PDA is funding an IR&D program to correlate CT data, density and mechanical/ thermal properties of advanced composites.

Computed tomography appears to have the potential of ultimately "driving" a thermostructural analysis if quantitative density data can be provided (1). Recent PDA studies indicate that quantitative CT density correlations are possible (2). This paper describes additional progress made in quantitatively assessing the density of various composites by CT and describes the calibration procedures necessary to achieve meaningful

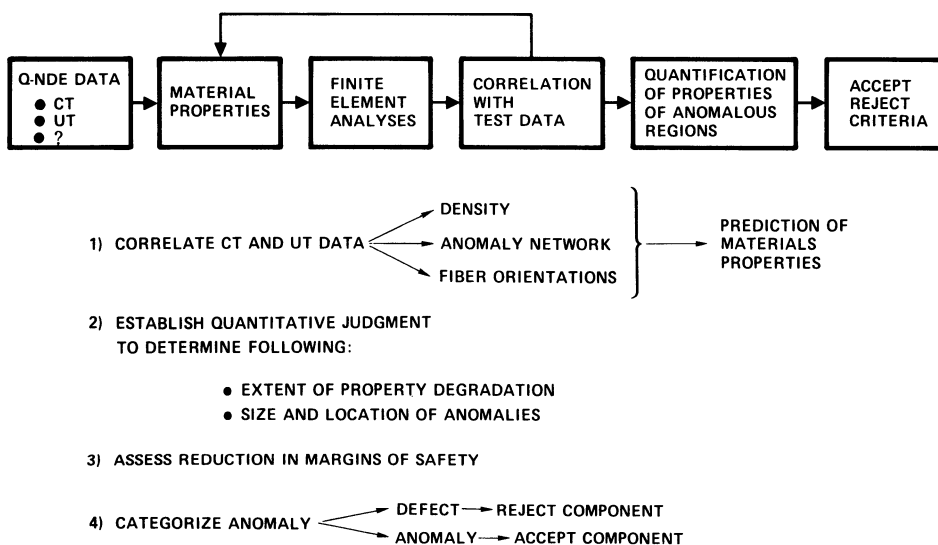


Figure 1. Quantitative NDE Accept/Reject Flow Chart

correlations between CT numbers and absolute density. Selected correlations of microstructural observations and CT images are presented as are studies concerning dimensional precision and resolution.

## CT NDE PROCEDURE

Computed Tomography scanning (also known as Computerized Axial Tomography- CAT Scanning) is an X-ray imaging technique. CT is based on the principle that radiation directed through a given volume of material will be absorbed to some degree by the material. The amount of absorption will be dependent on certain characteristics of the material including atomic number and physical density. CT images produced are of cross-sectional slices through the object which show the internal distribution of the X-ray attenuating properties of the material. CT procedures involve taking sophisticated measurements of radiation absorption and utilizing these measurements to obtain material characterization information.

The general procedure undertaken for a CT examination is outlined in Reference 3.

## DENSITY CALIBRATIONS

Critical to the CT examination process is the formulation of a mathematical relationship between measured absorption data and absolute material densities. Only with this step accurately completed, can CT NDE provide the desired level of quantitative material characterization.

The absorption/density relationship is a variable known to be dependent upon: the CT system, component or assembly geometry, component or assembly material (atomic number), scanning parameters (slice thickness, scan time, voltage, etc.), and CT system calibration. The effects of these parameters have been studied extensively in the medical community and can usually be accounted for by using proper calibration techniques.

The calibration process typically used by PDA to establish or verify the absorption/density relationship is described below:

- Preparation of the component for scanning includes positioning several calibration control rods within the component (typically aligned with the centerline).
- Control rods (normally numbering from 4 to 6) are materials of identical atomic number which span a range of densities and include at least one material similar to the actual component (i.e. similar in type of construction and absolute density).
- Accurate physical material density measurements are obtained for each control material.
- The absorption/density relationship is then defined by the control rod absorption magnitudes derived from the CT examination and the measured control densities, Figure 2.

Control specimens are usually prepared from actual composite hardware in order to provide absolute density standards during CT scanning. Refer to reference 3 for further details on density calibration.

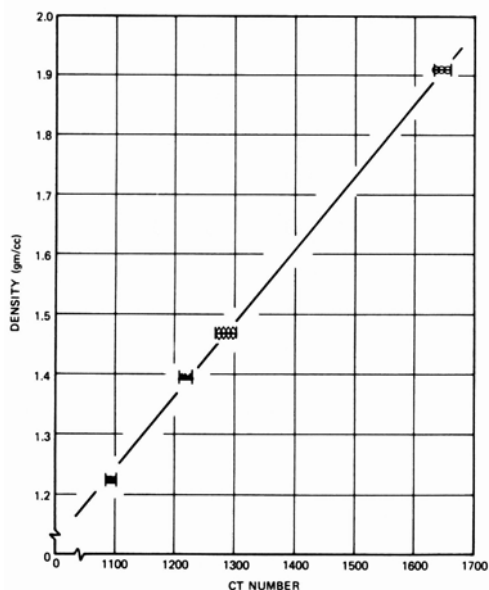


Figure 2. CT Number Versus Absolute Density

#### EXPERIMENTS: DESCRIPTION AND RESULTS

The following points were addressed in the current research described herein.

1. Effect of material composition on CT number/absolute density linear relationship. The validity of the CT number/absolute density relation is critical in the NDE of components with more than one material.
2. The precision of dimensional measurements. Direct dimensional measurements of complicated components via CT is a natural and powerful extension of the unique capabilities of CT.
3. The resolution and detectability limits of the CT system. Minimum flaw resolution and minimum flaw detection of a system will determine its applicability as a quantitative NDE tool.

PDA designed and fabricated a test article to address all three of these points. Called the Resolution Phantom, the test specimen consisted of a 6 inch (approx.) diameter by 1 inch thick graphite disk (Union Carbide AGSR; density = 1.60 g/cc nominal). A series of holes were drilled around the perimeter and at other select spots to accept a variety of polymeric, carbon, and other low atomic weight materials. Other holes were precisely located for dimensional and resolution investigations.

##### 1. Material composition effects on the CT number/absolute density relationship

Figure 3 describes the resolution phantom and the variety of polymeric, carbon and other materials utilized. Note that all the materials are comprised of relatively low and similar atomic number materials (i.e. all have components with atomic numbers of 9 or less). The lone exceptions are the glass filled epoxies (silicon has  $Z = 14$ ).

The compositions and densities of all the materials were precisely determined prior to scanning. The materials were then inserted into the graphite disk and the assembly inserted into the scanner. Parameters for the X-ray source were 140 KV, 140 mA, and 3 seconds exposure. A CT number/absolute density calibration curve was created from the data based upon the carbon and graphite disk only.

To assess the effect of material composition on the materials relation to the CT number/absolute density curve, the CT number for each specimen was extracted from the scan data. The specimen CT number was then plotted against its measured density on the CT number/absolute density curve created from the carbon/graphite data. The results are shown in Figure 4. Note that all the materials with the exception of the glass/epoxy materials

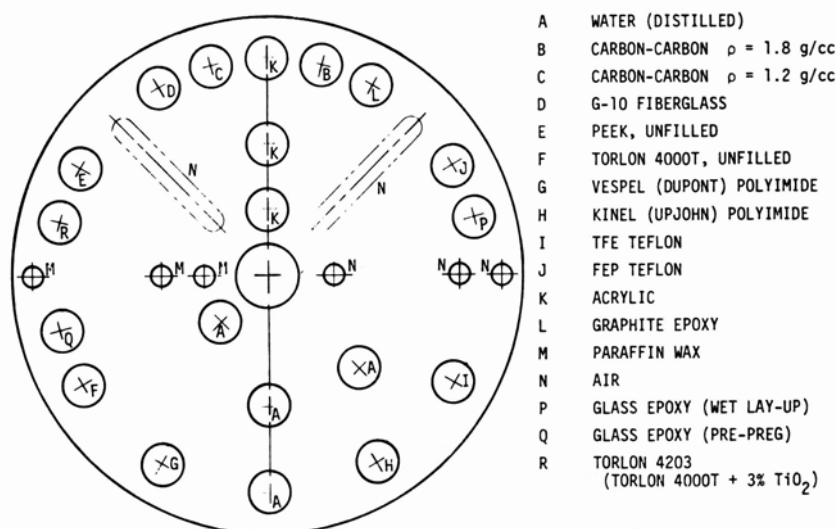


Figure 3. Resolution Phantom: Material Description

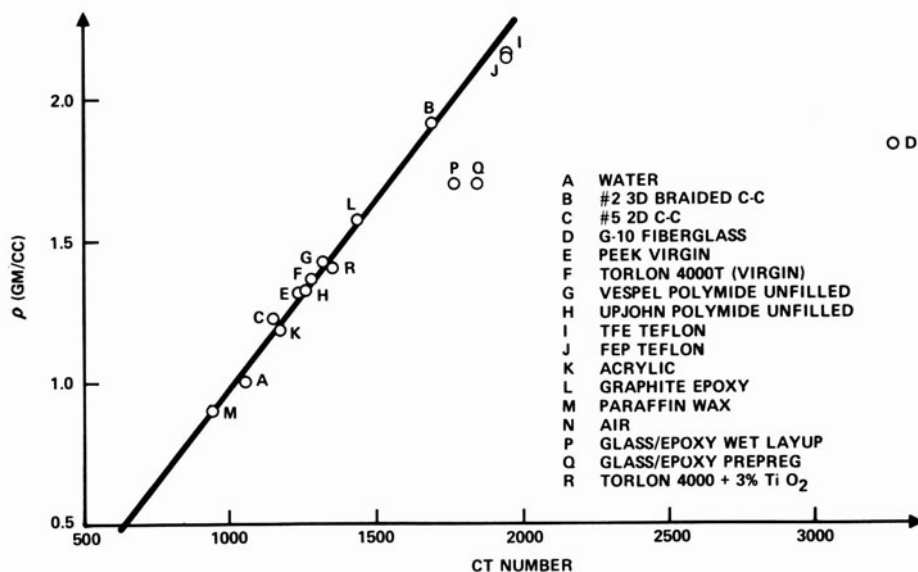


Figure 4. Resolution Phantom Material Study.  
CT Number Versus Absolute Density

fit very nicely upon this curve. The contribution of the silicon ( $Z = 14$ ) in the glass/epoxy materials is felt to be the major cause for these materials not correlating with the data; the attenuation of the X-rays is much higher in the glass/epoxy than the material density would dictate due to attenuation being a function of the atomic number to the fourth power (approx.) and the glass epoxy having a higher effective atomic number. All the other materials have similar effective atomic numbers and hence fall very close to the line.

## 2. Precision dimensional measurement

Figure 5 shows the dimensions between points used in the dimensional measurement study. The basic procedure for measurement entails counting the number of pixels between points and determining the characteristic pixel size based upon the scanning matrix size and the field of view of the CT system (both quantities are user defined on the GE9800 system). Counting the number of pixels between points is readily available due to the digital nature of the CT system and due to the CT number data being stored on a pixel by pixel basis. The characteristic dimension of the pixel is given by

$$d_{\text{pixel}} = \frac{\text{field of view size}}{\text{matrix length (or width)}}$$

The dimensional studies on the resolution phantom utilized a 7.09 inch (18 cm) field of view and a 512 x 512 matrix yielding pixels of .0138 x .0138 inches (.035 x .035 cm).

Definition of an edge was difficult owing to partial volume effects.<sup>2</sup> We defined an edge to be the pixel that had a CT number closest to the average CT number between the two materials in question (i.e. if air has a CT number of 0 and graphite a CT number of 1500, the edge is defined as the pixel with a CT number closest to 750).

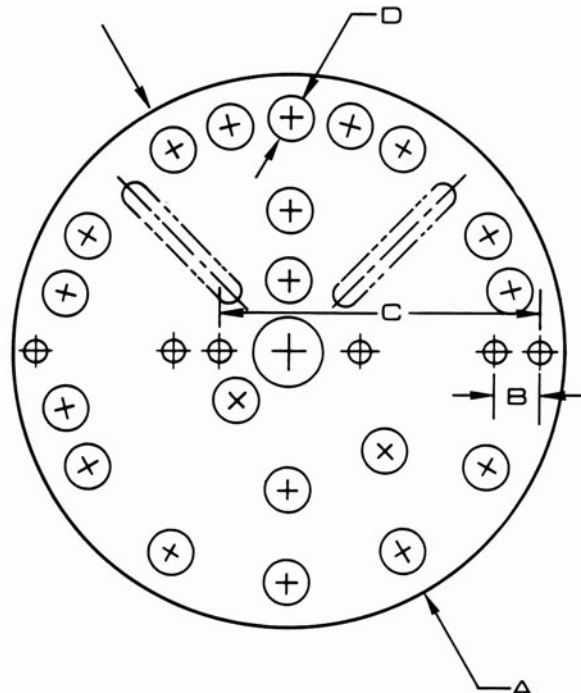


Figure 5. Dimensional Study

- 1 Pixels: Picture elements or segments of the CT image. The number of pixels in a scan slice is equal to the matrix, i.e. a 512 x 512 matrix has a total of 262,144 pixels.
- 2 Partial volume effect: Due to the finite size of a pixel, the CT system must average the properties within the pixel. Hence, at the transition between two or more materials, the CT number is weighted average of the materials.

Using this definition of an edge, measurements between the specific points on the resolution phantom were made. The results are summarized in Table 1.

Note the variance between CT measured and physically measured dimensions. We would expect a possible variance of .007 inches (half a pixel); variances of less than .007 are due to complimentary positioning of the edge pixels with respect to edge (i.e. the percentage of material 1 in one pixel is equal to the percentage of material 2 in the pixel at the other end of the desired dimension).

Table 1. Dimensional Variance CT Versus Physical Measurements

• CT PIXEL SIZE: 0.0138 INCHES (512 x 512; 18 CM FOV)					
LOCATION	DESCRIPTION	DIMENSIONS (INCHES)			
		PHYSICAL	CT	VARIANCE	
A	OUTER DIAMETER	5.975	5.982	0.007	
B	HOLE: CENTER TO CENTER (AIR TO AIR)	0.500	0.500	0.000	
C	HOLE: CENTER TO CENTER (PARAFFIN TO AIR)	3.500	3.495	0.005	
D	HOLE: DIAMETER OF ACRYLIC SPECIMEN	0.470	0.469	0.001	

### 3. Resolution/Detectability

Spatial resolution is defined in the CT context as the ability to distinguish two small high contrast objects located a small distance apart. By comparison, detectability is the ability to observe a difference or the effects of a difference between two high contrast objects but not necessarily distinguish it.

A series of small holes was drilled in the resolution phantom as shown in Figure 6. The presence of a 80 drill hole (.013 inches diameter) is detectable with the GE9800 system (.014 pixel size) as noted in Figure 7a. The visualization of the holes is improved with a change to gray scale colors and by applying image sharpening convolutions away from the GE9800 as shown in Figure 7b. Note the inherent danger of not being able to resolve the hole; if its presence was not known, one would be hard pressed to say that the flaw was actually a hole or just a low density region.

The hole triplets were intended to check the resolution. However, the inherent spacing between holes proved to be too thin in virtually all cases and was not a definitive test although the presence of a wall between the holes was detected. Figure 7 clearly resolves a circular hole of diameter .028 inches diameter.

## CONCLUSIONS

The experimental program undertaken has provided the following conclusions:

- Materials of similar effective atomic number can be directly correlated with the CT number/absolute density relationship.
- CT systems can be utilized to measure dimensions to an accuracy of 1/2 pixel. Improved accuracy can be achieved in post-scanning image processing by pixel multiplication and interpolation.
- The GE9800 system can detect flaws on the order of one pixel size. The resolution studies indicated 4.028 inch diameter hole limit to resolution.

In general X-ray CT can be used as a quantitative NDE tool for both flaw detection and dimensional studies. One can quantitatively characterize a flaw which is the first step in developing engineering tomography as a quantitative NDE tool.

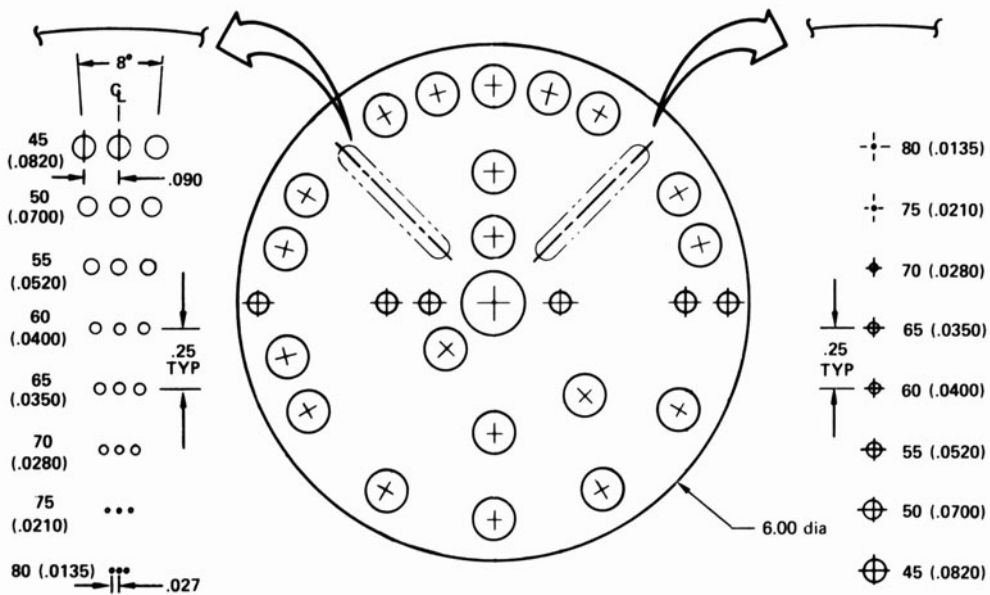


Figure 6. Resolution Phantom: Geometric Design

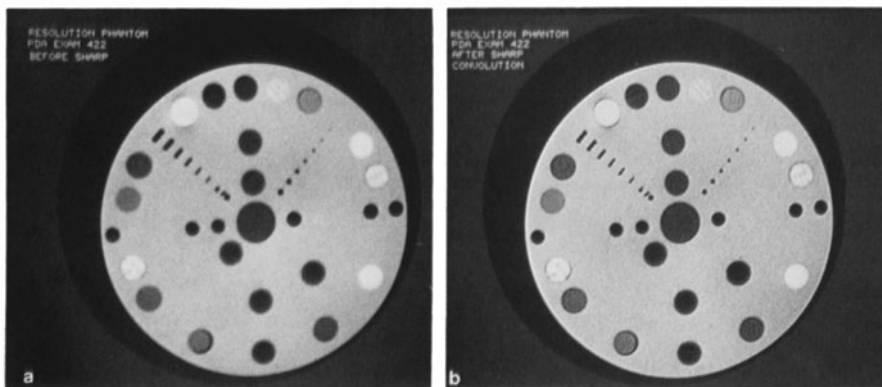


Figure 7. CT Images a) Without Enhancement  
b) With Enhancement.



## ACKNOWLEDGEMENTS

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## DISCUSSION

Mr. A. Notea (Israel Institute of Technology): In terms of the slide where you see very nicely the delaminations, about 25 slides back -- the thickness of the delamination is far, far off the real thickness between plies. You go back to the same phenomena I have been talking about previously. To correct for it, you have to go back into the memory of the computer, extract the numbers, and use a completely different algorithm. You cannot use the conventional element volumes to extract the real size of the flaw.

Mr. R. L. Hack (PDA Engineering): What he's talking about is cylinder with the involute plies and some noticeable delaminations. You can't use CT to really accurately predict the size of that delamination. You can detect that there is a delamination, but because of partial volume effects, you tend to spread the lower density over quite a few pixels and hence, you can't really achieve a good, accurate measure of that defect.

However, we have been able to see and measure defects on other parts that have more contrast than this part with better accuracy.

Mr. Notea: Another point is you should not mix so many materials in the same phantom because there is a memory. Between every point in the tomograph, there's the knowledge about the entire image itself due to the crossover of the beams. And once you mix so many together, it doesn't behave as in a practical object where you have only two or three.

Mr. Hack: I concur with that also. We have since been scolded for doing that, but I still feel it's valuable. They do line up very nicely, even in such a huge part.

From the Floor: On that involute cylinder, how big was that? And what was the pixel size?

Mr. Hack: The diameter of the cylinder was about eight inches. So the pixel size would have been approximately 15 to 20 mills.

- Mr. Robert E. Green: Since this is the last talk on the CAT scan with composites, I'd like to ask a question.  
Do you or does anyone else here have any thoughts on doing CAT scans inside an autoclave in the processing of composite material?
- Mr. Hack: I think we actually have. It's a matter of now trying to arrange for somebody to let us use their CAT scanner inside of an autoclave. (Laughter).
- Mr. Green: I mean outside the autoclave.
- Mr. Hack: You have a problem there, and I'll let -- Bill Pfeifer is in the back. I'll let him make a comment.  
I feel you're going to have a problem with penetration through the autoclave itself. The medical systems have a problem primarily because they utilize low-energy x-rays and they won't penetrate heavy steels or most other metals. A large high energy system, maybe like G.E.'s XIM System, if it was scaled up, might be capable of doing that.  
Do you have any comments, Bill?
- Mr. Bill Pfeifer (PDA Engineering): Yes. Only that we have done some sensitivity studies to be able to determine loss of contrast by running the experiment through the aluminum cylinder.  
In the petroleum industry, of course, they are looking at two-phase fluid flow through rock cores in a pressurized system. In the medical system, such as the 9800, you can get away with a certain thickness of aluminum. In the inspection of nozzles, you can go through some higher atomic number materials, also. But you've got a filter in the system now, so you have to pay attention to the physics and the atomic number of the material being penetrated.
- Mr. Hack: But as far as a means of monitoring the process in the autoclave, yes, we are aware that it would be a tremendous tool to do that.
- Mr. Oliver: Another comment on that is if you look at the contrast-to-noise ratio in an image, there is an optimum attenuation  $\text{Alpha L}$  product for that quantity, and if you have a high Z wall and then a low-density material on the inside, it's hard to get enough low-energy protons to get the contrast sensitivity that you want.